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MORTAR MIXTURES FOR THIN,
SKID RESISTANT CONCRETE
SURFACES

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16. Abstract <p>This paper describes work on the skid resistance properties of some fine aggregates available in Indiana, as an attempt to improve the driving safety characteristics of portland cement concrete pavements. For this purpose, mortar samples were tested under the British Polishing Machine to simulate the wearing action of the traffic, and by means of the Portable Skid-Resistance Tester, the best aggregate and mix proportions were selected to be applied as a very thin non-skid surface overlay for concrete pavements. The laboratory analysis considers the non-skid properties of the fine aggregates: natural sand, light-weight aggregate (expanded shale) and slag, after the surface texture of the overlay has been lost, which is the most critical situation.</p> <p>The cement modifiers Latex 464 and Rhoplex MC-76 were used to improve strength and bond capacity of the mortars. In this investigation, the adhesion developed by the thin overlay on a pavement surface was evaluated at the laboratory by means of the Pull Out Test; in this test the force required to pull out a section of the overlay is recorded as a result.</p>			
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Interim Report

MORTAR MIXTURES FOR THIN, SKID RESISTANT
CONCRETE SURFACES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

June 1, 1978

Project: C-36-53L

File: 9-6-12

The attached Interim Report is submitted on the HPR Part II Study titled "Thin Applied Surfacing for Improving Skid Resistance on Concrete Pavements". The title of the Report is "Mortar Mixtures for Thin, Skid Resistant Concrete Surfaces" and is the first Interim Report on the noted Study. The report has been prepared by Mr. Jorge Gomez-Dominguez, Graduate Instructor in Research on our staff under the direction of Professor C. F. Scholer.

The Report presents activity concerned with selection of a best aggregate and mix proportions for a thin overlay on concrete pavements. Materials considered included natural sand, expanded shale, and slag and several cement modifiers to improve strength and bonding of the mortars.

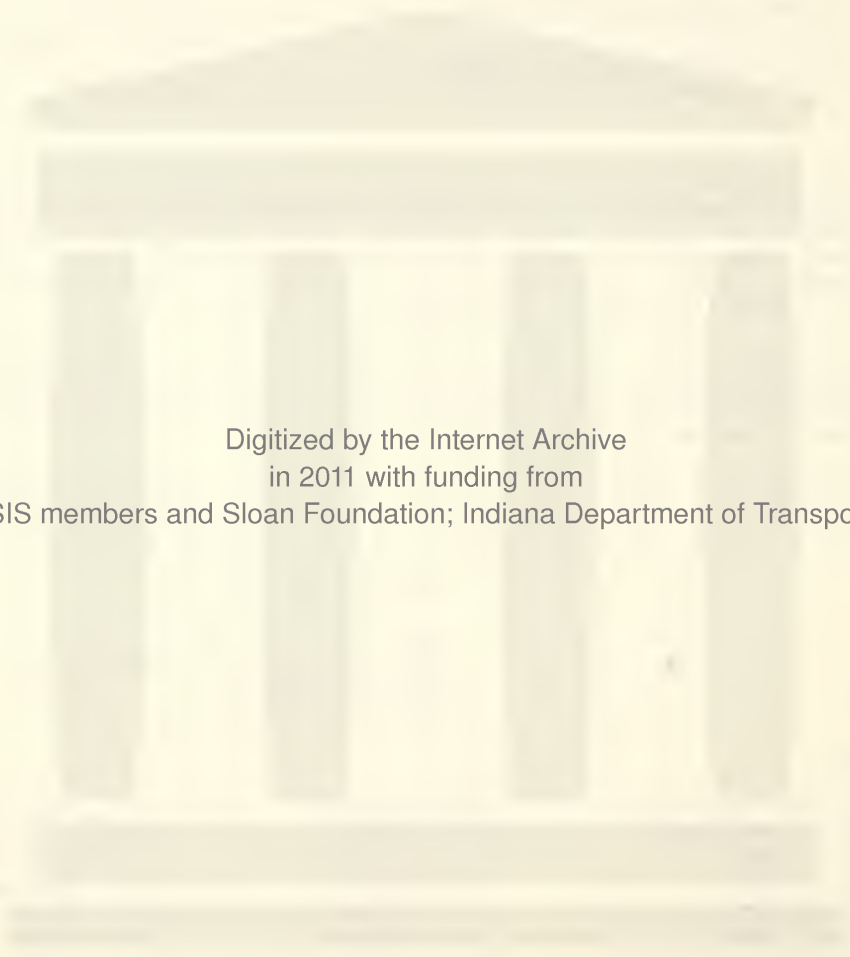
The Report is presented for review and acceptance as partial fulfillment of the objectives of the study. Upon such acceptance by the Advisory Board it will be forwarded to ISHC and FHWA for review and similar acceptance.

Respectfully submitted,

Harold L. Michael /ms
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Interim Report

MORTAR MIXTURES FOR THIN, SKID RESISTANT
CONCRETE SURFACES

by

Jorge Gomez-Dominguez
Graduate Research Assistant

Joint Highway Research Project

Project No.: C-36-53L

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Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the
Indiana State Highway Commission

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HIGHLIGHT SUMMARY

This paper describes work on the skid resistance properties of some fine aggregates available in Indiana, as an attempt to improve the driving safety characteristics of portland cement concrete pavements. For this purpose, mortar samples were tested under the British Polishing Machine to simulate the wearing action of the traffic, and by means of the Portable Skid-Resistance Tester, the best aggregate and mix proportions were selected to be applied as a very thin non-skid surface overlay for concrete pavements. The laboratory analysis considers the non-skid properties of the fine aggregates: natural sand, lightweight aggregate (expanded shale) and slag, after the surface texture of the overlay has been lost, which is the most critical situation.

The cement modifiers Latex 464 and Rhoplex MC-76 were used to improve strength and bond capacity of the mortars. In this investigation, the adhesion developed by the thin overlay on a pavement surface was evaluated at the laboratory by means of the Pull Out Test; in this test the force required to pull out a section of the overlay is recorded as a result.

CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

It has been recognized for many years that one of the major problems in highway engineering is to construct pavements that will achieve safe anti-skid characteristics under variable conditions and for a reasonable period of time. Most pavements develop adequate skid resistance in a dry state, but many become slippery when wet. It is extremely desirable to reduce this occurrence in order to obtain improved highway safety.

Much work has been done to develop good skid resistance on new pavements by using different finishing methods and surface textures as well as drainage. However, large traffic volumes result in a polishing action which considerably reduces the initial surface roughness {10}. Furthermore, such traffic combined with highway speeds reduce the distance between vehicles, demanding an optimum tire-pavement friction at all times to avoid accidents {10}. There are many other factors that could contribute to cause an accident by skidding; road defects, car defects, improper signing, weather, driver's experience, driver's health, and time and day of the week could be considered among those factors. Nevertheless, Mills

and Shelton {1} and Anon {2} have reported that skidding was considered the primary cause of accidents in many instances.

Most of the states in this country have carried out programs on skid resistance. Some of them have developed their own methods and devices to determine the skidding characteristics of surfaces. Due to the complexity of the problem, poor correlation between the measurements taken in the laboratory and those taken in the field remains as a problem to solve. Unfortunately, the skid resistance property of a surface cannot be described by a single parameter. A seemingly endless list of parameters exists including those pertaining to the kind of aggregate, the binder, traffic, age of surface and actual condition of the surface play an important role on the final evaluation. It was felt that the control of a laboratory investigation permitted a more accurate evaluation of the basic factors contributing to slipperiness of pavement surfaces. Those parameters identified as significant to good skid resistance in the laboratory would then be evaluated and hopefully later incorporated into field evaluations.

The work set forth in this paper is a part of a program concerned with the practical aspect of the problem. It is intended to bring the worn or polished pavement surfaces back to a good anti-skid performance by using a very thin overlay, or to improve new construction of concrete pavement by means of a thin surface layer made of select material.

1.2 Literature Review

Considerable work has been done pertaining to problems of pavement-skid resistance. Much has dealt with bituminous pavement surfaces, however, valuable work has been done on portland cement concrete pavements.

Field testing was the first step engineers made in an effort to measure the potential hazard of skidding on roads {3}. From those tests in 1934, Moyer {4} in Iowa reported that for bituminous pavements, the use of limestone dust and limestone aggregate resulted in surfaces that develop low coefficients of friction when the wheels of a test vehicle are locked at a given speed.

The first detailed report on the automobile stopping-distance method of skid testing resulted from work conducted in Virginia by T.E. Shelborne and R.L. Sheppe {5} in 1948. They reported surfaces having a harsh, gritty, "sandpaper" texture were found to have short stopping distances. In 1950, J.F. McLaughlin "conducted research on skid resistance for the Joint Highway Research Project in Indiana". From 1951 to 1956 field observations made by D.L. Grunan and H.L. Michael yielded conclusions which included the following items {6}.

1. A thin application of rock asphalt is a good but only temporary method of de-slicking a pavement.

2. Portland cement concrete surfaces provide relatively good skid characteristics but are subject to polishing by traffic during the first few years of their life.
3. Although it cannot be considered conclusive because of the small number of roads tested, surfaces constructed with silica sand gave good results, comparable to rock asphalt.

As the field tests increased in number {7} the reports about critical situations became more and more complete, but the control and consistency inherent in a laboratory investigation still was missing.

J.W. Shupe and W.H. Goetz, of the Joint Highway Research Project, developed in 1958 a laboratory skid-test apparatus to evaluate both laboratory specimens and cores taken from the highway {8} in an effort to relate the basic properties of the materials to the skid resistance of test specimens composed of these materials. An extensive program was carried out in which both portland cement concrete and bituminous specimens were evaluated in the wet condition after a simulated polishing action. About the same time the University of Tennessee {19} and the University of Kentucky {20} developed their own equipment to investigate the potential slipperiness of paving mixtures.

Once engineers developed the laboratory skid test equipment, they started explaining and correcting the problems faced in the field.

Relatively little work has been done in the specific subject of thin surfacing methods for improving skid resistance of portland cement concrete pavements. Considerably more has been done in the general field of skid resistance itself; namely, polishing characteristics of mineral aggregates {9}, {10}, frictional characteristics between tire and pavement surface {11}, {12}, final texturing of the pavement {13}, and field techniques to evaluate skid resistance properties {14}.

For portland cement concretes, the coarse aggregate is protected by the mortar which plays an important role in the skid resistance properties of the pavement surface. This element presents a large area available for friction, on the other hand the coarse aggregate appears randomly at the surface and becomes less important once it has been polished.

Laboratory results {10} indicate that the use of resistant fine aggregate provides good anti-skid properties most of the time, hence the use of soft polish susceptible materials should be avoided in fine aggregate. Limestones have developed poor reputation with regard to their resistance to polishing, however, there is some variability in that characteristic depending upon the type of limestone {15}.

It is well recognized that the mix composition {16} has a great influence in the future performance of the concrete pavement, since it will fix all the parameters involved that yield the final product.

Recently Calley, Christensen and Nowless {10} reported that for concretes with an increase in cement content or a decrease in water-cement ratio the rate of wear decreases. They also concluded that generally the wear resistance was increased as the percent of sand was increased from 34 to 42 percent.

Final texture of the concrete pavement is an important factor to consider when dealing with skid resistance {13}. However, this aspect will not be considered in this investigation.

1.3 Statement of the Purpose

This investigation was designed to deliver data on the skid resistance properties of certain natural and manufactured fine aggregates which are, or could be, useful in the construction or repair of Indiana roads. The results would serve as input to field evaluation of very thin overlays for the purpose of improved skid resistance.

The relationships between skid characteristics, mix composition, and polishing characteristics of the aggregates needed to be evaluated in order to develop mixes for field applications.

1.4 Approach used in this work

This work considers the anti-skid properties of the fine aggregate in a portland cement mortar once the surface texture of a thin surface layer on concrete pavements has been lost due to wear and polishing. Figure 1 shows a very young concrete pavement in U.S. 52 By-Pass, West Lafayette, Indiana illustrating the effects of the traffic.

The abrasion phenomenon on the roads is quite complicated, since many factors are involved besides those of the traffic. Figure 2 shows that sand and pebbles standing on the road increase the rate of wear.

The British Polishing Machine affords a laboratory method to simulate the polishing action of the traffic, accelerating such phenomenon.

In addition, the portable skid-resistance tester provides a good method of checking the resistance of wet surfaces to skidding. Both types of apparatus were used in this investigation and their description is given in the next chapter.



Figure 1. Polishing effects of the traffic



Figure 2. Inert material standing on the road

CHAPTER II

MATERIALS AND APPARATUS

2.1 Materials

2.1.1 Cement

Type I portland cement from a single source was used in all mortars.

2.1.2 Fine Aggregates

Three fine aggregates were used to start the investigation, and gradation characteristics were checked several times in order to minimize variations in grading within each aggregate. The fine aggregates were: natural sand, lightweight aggregate (expanded shale), and slag.

The natural sand was a local glacial - alluvial sand, its gradation is given in Table 1. The fineness modulus was 2.64.

Additional determinations on the properties of the natural sand were: bulk specific gravity (SSD), 2.52, and absorption, 2.50%, both in accordance with ASTM Designation: C 128-68. Dry rodded unit weight, $1,760 \text{ Kg/m}^3$ (110 lb/ft^3), according with ASTM Designation: C 29-71. Total insoluble residue 63% ASTM D 3042-72. Since the natural sand was the most heterogeneous aggregate, Table 2 summarizes the petrographic characteristics of a representative sample.

Table 1. Sieve Analysis of Natural Sand

Sieve number (mm)	Cumulative percentage retained
4 (4.75)	0.1
8 (2.36)	10.0
16 (1.18)	27.5
30 (0.60)	51.0
50 (0.30)	83.0
100 (0.15)	93.0

Table 2. Petrographic Analysis of Natural Sand

% of Particles Retained on Sieves (*)										On the Whole Sample (**)					
Constituents	No 4	No 8	No 16	No 30	No 50	No 100	No 200	Physical Quality			Chemical Quality				
								S	F	P	I	D	T		
Limestone & dolo.	54.0	56.3	49.4	17.4	17.2	13.6	13.3	26.1	4.3	1.3	31.7			31.7	31.7
Qtz & Quartzite	14.0	22.6	28.3	54.7	52.9	59.7	64.3	37.7	4.3	0.2	42.2			42.2	42.2
Granite	11.0	10.6	18.3	21.4	20.0	8.6	4.5	12.0	1.6	0.2	13.8			13.8	13.8
Basalt	5.3	3.3	2.7	0.9				1.2	0.4	0.1	1.7			1.7	1.7
Shale	1.4	2.0						0.1	0.3		0.4			0.4	0.4
Chert	5.3	0.4						0.5	0.3			0.8		0.8	0.8
Gneiss	2.7	1.4	0.6	0.3	0.6			0.7	0.1						0.8
Calcite lumps	3.3									0.5	0.5			0.5	0.5
Sandstone	3.0	2.4		4.7	8.6	13.2	5.4	3.7	1.2	0.5	5.4			5.4	5.4
Claystone		1.0	0.7					0.1	0.1	0.2				0.2	0.2
Iron oxide				0.6	0.7					0.2		0.2		0.2	0.2
Chlorite, biotite, mica						4.9	8.3	0.8	0.6	0.5	1.9			1.9	1.9
Feldspar							4.2	0.4			0.4			0.4	0.4
TOTAL	100	100	100	100	100	100	100	83.3	13.1	3.6	99.0	1.0		100.0	100.0

(*) Based on count of 350 particles in each sieve

(**) S = satisfactory; F = fair; P = poor; I = innocuous; D = deleterious; T = total constituent

The lightweight aggregate was an expanded shale from Brooklyn, Indiana. The gradation is given in Table 3. The fineness modulus was 3.0 (by weight).

Additional determinations of aggregate properties were: dry loose unit weight, 954 Kg/m^3 (59.6 lb/ft^3), bulk specific gravity (SSD), 1.77, and absorption 15%, total insoluble residue 90%, all in accordance with their respective ASTM Specifications.

The expanded shale was a relatively uniform product, gray to brown in color, with hard and vesicular particles retained on sieve No. 4. From sieve No. 8 to No. 30, it was found that about 67% of the particles were hard, and about 32% were firm to fragile with numerous vesicular holes up to 0.7 mm in diameter. For the fractions retained on the No. 50 and No. 100 sieves, about 58% were hard nonvesicular particles, 35% were firm to fragile particles, and minor percentages of sandstone, quartz and coal were found. For the No. 200 sieve 40% of the particles were hard and gray to dark brown in color, 50% were firm to fragile, also minor percentages of quartz, sandstone and coal were found.

The slag was from blast furnaces in northwestern Indiana. The gradation is given in Table 4. The fineness modulus was 2.97. Additional properties were: bulk specific gravity (SSD), 2.6, absorption 4%, dry loose unit weight, 1704 Kg/m^3 (106 lb/ft^3), and total insoluble residue 75%.

In general, the slag is an excellent aggregate consisting of hard particles in all the different sizes, having a rough

Table 3. Sieve Analysis of Lightweight Aggregate

Sieve number (mm)	Cumulative percentage retained
4 (4.75)	2.8
8 (2.36)	17.1
16 (1.18)	46.6
30 (0.60)	67.3
50 (0.30)	79.6
100 (0.15)	92.3

Table 4. Sieve Analysis of Slag

Sieve number (mm)	Cumulative percentage retained
4 (4.75)	1.0
8 (2.36)	20.0
16 (1.18)	42.3
30 (0.60)	64.5
50 (0.30)	79.0
100 (0.15)	91.0

texture and a gray color.

For the sieves number 4, 8, and 16 about 70% of the retained particles have vesicular cavities from 0.2 mm to 1.7 mm in diameter. Vesicular cavities diminish for smaller particles from 0.15 mm to none for sieve No. 200. Under the microscope, particles retained on the No. 30 and smaller sieves have the appearance of granites but with irregular shape because of their vesicular texture.

2.1.3 Admixtures

In an effort to improve the bond and strength characteristics of the normal mortars, two admixtures were used; they were: Dow latex 464 and an acrylic Rhoplex MC-76. Both admixtures are defined as polymer modifiers of portland cement mortars. Essentially they are polymers dispersed in water having the appearance of a white milky liquid.

The latex 464 has been developed by the Dow Chemical Company and supplied by Dow Chemical at Midland, Michigan. Typical properties for the Dow Latex 464 are given in Table 5.

The Rhoplex MC-76, acrylic polymer, is produced by Rohm and Haas Company, Philadelphia. Some of its properties are given in Table 6. It was used because of its recommendation for pneumatic applications.

2.1.4 Water

Ordinary tap water was used in all the mixes.

Table 5. Typical Properties of Latex 464

Property *	Latex 464
Polymer Type	Saran
Stabilizer	Non-ionic
Percent Solids	50%
Specific gravity (25°C)	1.23
Weight per gallon (lbs @ 25°C)	10.25
pH	2.0
Particle Size Range (angstrom)	1400
Surface Tension at 25°C (Dynes/cm ²)	33
Freeze-thaw stability	none (alone)
Specific gravity of Latex Solids	1.60
Film forming	
(25°C)	yes
(4°C)	no
Shelf Life	6 months

* Supplied by the Dow Chemical Company

Table 6. Properties of Rhoplex MC-76

Property *	Rhoplex MC-76
Solids Content	46 to 48%
pH (when packed)	9.5 to 10.0
Specific Gravity	1.059
Weight per gallon	8.8 lbs
Freeze-thaw Stability	5 cycles
Minimum film formation Temperature	10 to 12°C

* Supplied by Rohm and Haas Company

2.2 Apparatus

Three different types of apparatus were used throughout the investigation to accomplish for mixing of mortars, polishing and skid testing of mortar specimens.

2.2.1 Mixing

A standard Hobart mixer, type N-50, capacity approximately 4-3/4 liters was used in mixing the mortars; Figure 3.

2.2.2 Polishing

To obtain a rapid rate of polishing action, the British Polishing machine was used; Figures 4 and 5. The machine will permit the mounting of fourteen specimens forming a continuous surface which is in contact with an 8 inch diameter pneumatic tire with an inflation pressure of 45 lb/in². During a period of eight hours silicon carbide and water are fed directly onto the continuous mortar surface just before it passes under the tire. An arm with a weight presses the tire onto the continuous surface with a normal load of 88 lb. The continuous mortar surface is driven at 320 rev/min by a 3/4 h.p. motor.

2.2.3 Skid Testing

The portable skid-resistance tester, Figure 6, was used to evaluate the resistance to skid of the specimens, after they have been polished by the accelerate polishing machine. Complete description of the apparatus is given elsewhere {17}, along with instructions to carry out the

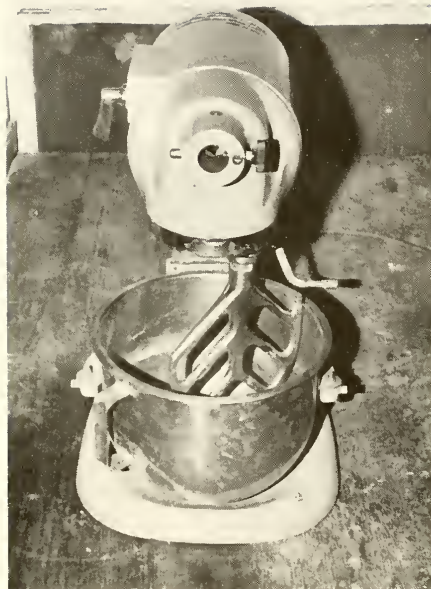


Figure 3. Mixing Apparatus

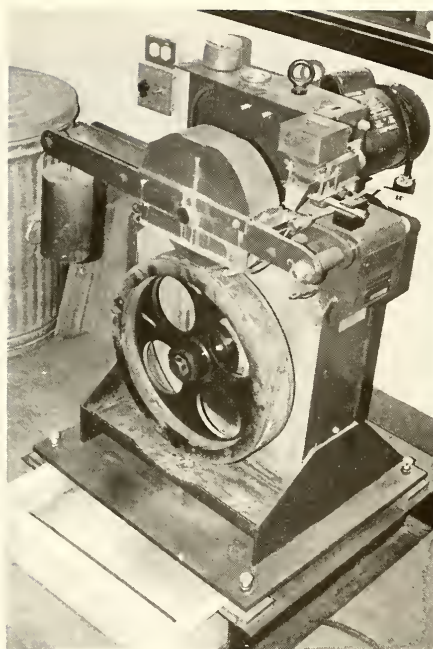


Figure 4. Polishing machine

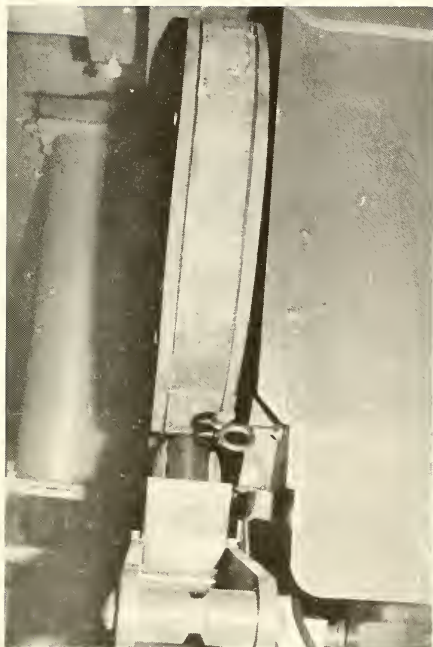


Figure 5. Close up polishing machine

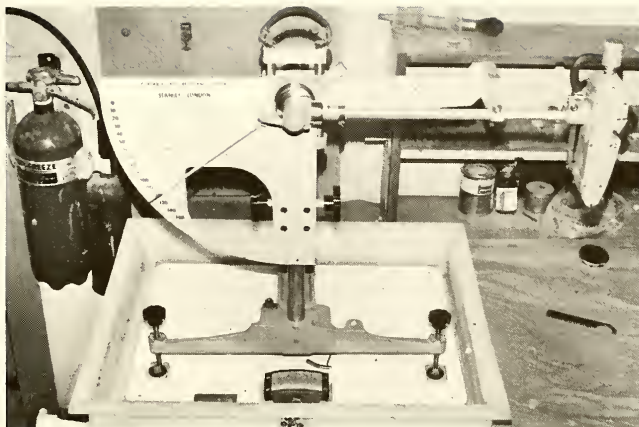


Figure 6. The Portable Skid-Resistance Tester

tests {18}. Briefly, in this apparatus a rubber slider, mounted on the end of a pendulum is passed across the wetted surface of the specimen by releasing the pendulum arm from the right hand, approximately in a horizontal position and a pointer carried by the pendulum will finally point out the correspondent reading on a left hand scale.

CHAPTER III

EXPERIMENTAL INVESTIGATION

In this chapter the skid resistant properties of several fine aggregates are discussed. A sequential statistical approach was used to interpret the different physical properties involved in the process of selecting acceptable mixes to be applied as thin surfacings for improving skid resistance of concrete pavements.

General details concerning the procedures followed to prepare the samples used throughout the investigation are given, along with comments on the methods of testing, and other pertinent information.

3.1 Experimental Method

The laboratory work was carried out considering that the surfacing treatment on slippery pavements would be thin, namely less than half an inch thick. Therefore, only aggregates with sand gradations were used.

The factors and levels initially investigated in order to gain a better understanding of the skid phenomenon were

Three fine aggregates (sands):

- a) Natural sand
- b) Lightweight aggregate
- c) Slag

Two admixtures (cement mortar modifiers):

- a) Rhoplex MC-76, acrylic polymer
- b) Dow latex 464, saran latex polymer

Two water to cement ratios (by weight):

- a) $W/C = 0.40$
- b) $W/C = 0.45$

Two sand to cement ratios (n), (by weight):

- a) $n = 2.0$
- b) $n = 3.0$

The factor type of aggregate (TYPEAG) was defined without including the limestone aggregate which is common in Indiana, since it has been recognized that limestones polish relatively rapid and their skid resistance is generally low. On the other hand, natural sand is generally available in Indiana and it has been reported that many limestone pavements developed better skid resistance properties when natural sand was used as fine aggregate [15]. The lightweight aggregate has not been used in concrete pavements. Slag has been reported as satisfactory when used in pavements in the State of Indiana.

The factor admixture (ADMIX) was included considering that something might be done to improve the bonding capacity of the thin overlay.

The factors water to cement ratio (WCRATIO) and sand to cement ratio (SCRATIO) were results of considerable preliminary work; this work was done considering the next important goals:

1. To set up common levels of study in order to establish a comparison of results for all the aggregates used.
2. Look for feasibility to apply the mixes at the field.
3. Establish critical levels in accordance with 1 and 2, which could yield normal, rich and poor mixes, in order to study the skid phenomenon within such conditions.

As outlined at the beginning of this chapter, three types of fine aggregates were included in the analysis; since there was no way to describe them numerically, three qualitative levels were used in the statistical analysis. The other factors had two quantitative levels each.

The main purposes of the basic experiment were to find out what skid resistance could be expected for the different mixes resulted from a factorial design, and illustrate the effects of the factors.

The response variable was the skid resistance number for each specimen; such number was recorded from the Portable Skid Tester.

A full $3 \times 2 \times 2 \times 2$ factorial experiment was performed, adding 4 specimens for replicates, the total number of specimens made were 96. A total randomization for casting the specimens was not possible because appreciable amounts of mix could be wasted by the end of the work and, since

admixtures had to be used, such a type of experiment becomes expensive. However, the samples were cast in as random an order as feasible.

3.2 Details of mix design

The next paragraphs illustrate the method of mix design for the mortars.

Assume that a mortar was to be designed in which the proportion of sand (slag) to cement ratio was 2.5, and for which the water to cement ratio was 0.45, the volume of each ingredient in a 1 sack of cement batch was computed as shown in Table 7.

Table 7. Sample mix design

	Water	Sand	Cement	Total
Proportions by weight	0.45	2.5	1	
Wt for 1 sack batch, lb	$0.45 \times 94 = 42.3$	$2.5 \times 94 = 235$	94	
Specific gravity (Sp Gr)	1.00	2.60	3.15	
Cu ft = $\frac{\text{Wt}}{62.4 \times \text{Sp Gr}}$	0.68	1.45	0.48	2.61

If an admixture were to be used, say Rhoplex MC-76 (47% solids) at 20% of the weight of the cement, a correction should be made to account for the water provided by the admixture:

$$\text{Water for mixing} = 42.3 - 0.20 \times 94 = 23.5 \text{ lb}$$

3.3 Details of mixing and casting

A standard Hobart mixer was used in mixing the mortars. The sand was first placed into the mixer bowl. The mixer was started and the water for absorption was added and mixed until the water was dispersed. Next, mixer was stopped for a 10 second period to allow absorption to take place. The cement was added and mixed, next the mixing water and the admixture with antifoamer, if any, were added. A 120 second period was used for the initial mixing, followed by a waiting period of 90 seconds. Finally, a second mixing period of 120 seconds completed the process.

The mixing was done at the medium speed setting to avoid excessive air voids. Whenever the mixer was stopped, the mixer bowl was covered with a wet towel to minimize evaporation. The mixing procedure just described differs from that given the standard (ASTM C 305-65) because the mortars were designed to be reproduced at the field.

After the mixing was complete, the specimens were immediately cast. Figure 7 shows a mold and a set of tools used for casting. The specimens were cast in two layers; each layer was tamped 27 times. Figure 8 shows a skid specimen. Three wires 1.2 mm in diameter were used as reinforcement, as shown in Figure 9. After casting, the specimens were wrapped with plastic and a wet towel placed over them and kept at normal temperature until demolding.

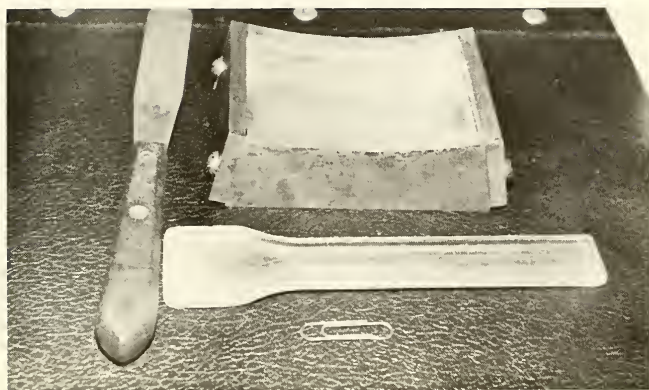


Figure 7. Set of tools for casting skid specimens

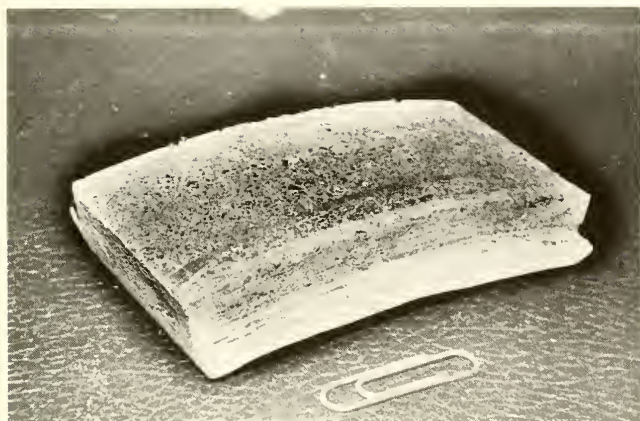


Figure 3. Skid specimen

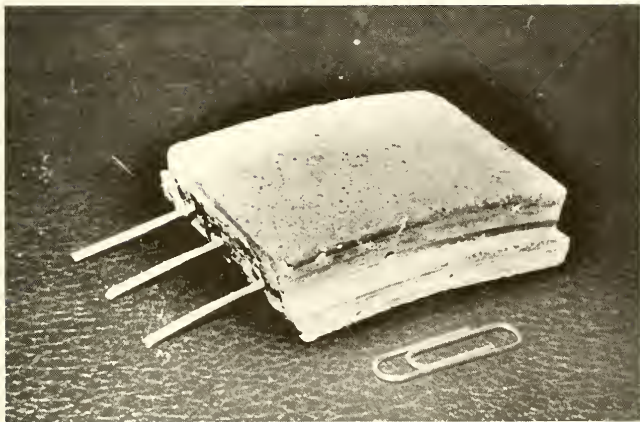


Figure 9. Cross section of skid specimen

3.4 Initial results

After 28 days of moist curing conditions, the specimens were tested under the British Polishing machine. Eight hours of continuous abrasion was allowed to wear out the surfaces of each fourteen specimen series.

After polishing, the specimens were tested individually under the portable skid tester. Water was spread over the contact area with a plastic bottle between each swing of the pendulum. The reading indicated by the pointer was noted. Swings were repeated until three successive readings were constant; normally this was accomplished with 6 to 9 readings. The constant readings for each specimen that turned out to be the lowest ones are summarized in Table 8. The numbers in the parentheses are averages. For skid resistant, the higher the number the better the anti-skid properties. The admixtures Rhoplex MC-76 and Dow latex 464 were used at 20% of the weight of the cement. This dosage was within the range recommended by each manufacturer.

3.4.1 Analysis of variance for the initial results

A Foster-Burr Test for homogeneity of variances was performed on the data noted in Table 8. A sample variance taking the value zero does not disrupt this test. The test resulted in accepting the hypothesis that within sample, variances were equal at 0.05 level of significance. With these variances determined to be equal, it was possible to proceed with the analysis of the data using the factorial model.

Table 8. Basic Skid Resistance Results

Sand-Cement ratio (n)

n = 3

n = 2

Admixture	Nat. Sand			Lightweight			Slag			Nat. Sand			Lightweight			Slag		
	w/c			w/c			w/c			w/c			w/c			w/c		
	0.40	0.45		0.40	0.45		0.40	0.45		0.40	0.45		0.40	0.45		0.40	0.45	
Latex*	30	32		35	36		35	30		30	33		39	40		38	27	
	28	39		34	37		36	29		30	35		37	33		38	30	
	29	31		37	37		33	29		30	32		34	36		38	33	
	27	37		40	37		36	33		30	35		45	41		42	40	
	(31.00) (34.75) (36.50) (36.75) (37.50) (38.75) (39.00) (40.25)																	
Rhoplex*	33	31		36	36		31	31		31	31		38	33		31	37	
	32	29		38	35		32	28		31	31		38	38		33	38	
	35	32		38	33		28	31		31	31		35	37		31	37	
	34	32		40	36		29	33		32	31		36	34		31	28	
	(33.50) (31.00) (38.00) (35.00) (30.00) (30.75)																	

* At 20% by weight of cement

Hence, an analysis of variance (see Appendix) was performed on the response variable skid resistance (SKIDRES) with the data of Table 8. To accomplish this purpose, the Statistical Package for the Social Sciences (SPSS) available at Purdue University was used.

The F-Test shown in the ANOVA table indicates that at 0.05 level there were no significant interactions between the four factors, in fact those effects were so low that they were not pooled to compute the mean square for error.

On the other hand, there were very significant interactions between the admixture (ADMIX), the type of aggregate (TYPEAG) and the water to cement ratio (WCRATIO) used in the experiment. The presence of the three-factor interactions implies that at least some of the specific two-factor interactions differ, depending on the level of the third factor. Furthermore, the interpretation of the main effects became difficult since at least some of the effects depend on the level of the other two factors. Therefore, the model turned out to be difficult to interpret and only an analysis of the individual results of each mix combination supported with the understanding of their physical behavior could be obtained for the desired information.

The technique used to detect the best levels (best mixes) of the parameters was a series of Newman-Keuls comparisons of means based on the ANOVA results.

The Newman-Keuls Table (see Appendix) for the 24 means of Table 8 indicates that there is no significant difference

between the highest mean (39.00) and all the lower ones down to the mean ranked in the fifteenth place (32.50), and also there are no significant differences among all of them. The highest mean was yielded by the slag with a sand to cement ratio of 3, a water to cement ratio of 0.40 and latex as admixture. The second higher value was reached by the lightweight aggregate with a sand to cement ratio of 3, a water to cement ratio of 0.40 and latex as admixture. Statistically, any of the mixes which did not show significant differences could be selected regardless of their skid resistant value. However, the future performance of the mixes would depend on such selection.

The Analysis of Variance Table also suggests that the sand to cement ratio (SCRATIO) factor not included in the significant three-way interactions could be assumed constant when taking averages of means for the remaining factors. For example, for the natural sand the average over the sand to cement ratio, the admixture latex, and a water to cement ratio of 0.40 is 30.5. The Newman-Keuls Table for the 12 means resulted from this approach indicates that the first, second, third, and fifth places belong to the lightweight aggregate. The fourth, seventh, ninth, and eleventh places belong to slag. The places sixth, eighth, tenth, and twelfth belong to the natural sand.

In addition with little variation, the higher skid resistance values were yielded for a water to cement ratio of 0.40, and with some consistency the admixture latex yielded

most of the higher skid numbers. Without any doubt, the most important factor to consider is the type of aggregate (TYPEAG) since it appears to be significant in the multiple interactions and in the main effects.

Some additional information can be obtained from a sequential Newman-Keuls Comparison of the means averaged for each factor maintaining the others as constants, although this information should be interpreted carefully because of the presence of the significant three-factor interactions.

In the Appendix, the Newman-Keuls Table for detecting the best aggregate indicates that there was no significant difference between the first (37.13) and the second (36.56) ranked means, both of them belong to the lightweight aggregate; the first mean was obtained over the sand to cement ratio of 3, and the second one over the sand to cement ratio of 2. The third place was occupied by the slag over the sand to cement ratio of 3. The Newman-Keuls Table for detecting the best admixture indicates that the Rhoplex and the latex yield skid numbers that are nearly equal, however, the averages of the means based on 48 observations differ at 0.05 level. The latex yielded the highest mean average (34.65).

Finally, a similar comparison of averaged means indicates that there is no significant difference between the skid means for the water to cement ratios of 0.40 and 0.45.

The previous information led to the following conclusions regarding skid resistance:

1. Lightweight aggregate and slag yielded the higher skid resistance numbers.
2. It was noticed that slag behaves better with the sand to cement ratio of 3, and the lightweight behaves well either with a ratio of 3 or with a ratio of 2.
3. It was noticed that the influence of the water to cement ratio was not highly significant for the levels of this experiment.
4. With some consistency, the higher skid numbers were reached with the mixes including latex as admixture.

3.4.2 Workability of the initial mixes

From the laboratory work it was noticed that the mixes made with the sand to cement ratio of 3 and a water to cement ratio of 0.40 were dry and difficult to work with, the water to cement ratio of 0.45 provided better consistency, but still the mixes were considered somewhat dry.

For the sand to cement ratios of 2 and a water to cement ratio of 0.40 the mixes were normal, and with a ratio of 0.45 they were wet, the only exception was for the lightweight aggregate which yielded good consistency for the water to cement ratio of 0.45 and fair mixes for the ratio of 0.40.

3.4.3 Strength of the initial mixes

An improvement in compressive strength was observed in the mixes when cement modifiers were used. Mixes with Dow latex 464 at 20% of the weight of the cement gained about 25% more strength than those unmodified. The mixes made with Rhoplex MC-76 at the same level increased their strength about 7% over the unmodified mortars, but some inconsistency was shown.

3.4.4 Skid resistance of unmodified mixes

In some instances, the skid numbers for the unmodified mixes in this initial series of tests were slightly higher than those for the modified mixes. Data for the unmodified mixes are given in Table 9. It was thought that stronger mixes sacrificing several skid units will perform better under intensive traffic.

3.5 Final Study

The next step in this work was to try to optimize strength and workability of the mixes without introducing any detrimental effects on their skid resistant properties. To accomplish this goal, a new series of mixes were considered for further analysis.

The new factors and levels considered were

Two fine aggregates (sands):

- a) Lightweight aggregate
- b) Slag

One admixture:

- a) Dow latex 464 at 10, 20, 30,
40, 45% of the weight of the
cement

One water to cement ratio (by weight):

- a) $w/c = 0.45$

Four sand to cement ratios (by weight):

- a) $n = 1.5$
- b) $n = 2.0$
- c) $n = 2.5$
- d) $n = 2.75$

The factor type of aggregate (TYPEAG) has been reduced to two qualitative levels, lightweight aggregate and slag, since they were consistent as far as skid resistance is concerned.

Most of the higher skid numbers were reached with the mixes including latex as admixture, and also better strength was gained. In this part of the work the purpose was to investigate the effects of the latex in the skid resistance of the mortars and in the strength.

Important considerations have to be made about the new levels of the factors: water to cement ratio and sand to cement ratio, since they are going to influence skid resistance, strength and workability.

It is well known that the lower the water cement ratio the higher the strength but it would be difficult to work with low ratios in the field because the mixes tend to be

stiff; in addition, thin surfacings present the risk of losing water very soon under warm or windy weather conditions, which would be detrimental as far as hydration of the cement. On the other hand, high water to cement ratios will yield weaker mortars. Therefore, a reasonable ratio to work with would be 0.45.

The sand to cement ratios of 1.5 and 2.0 were fixed for the lightweight aggregate, taking into account that low ratios will help this aggregate to gain more strength since more cement is used, besides good workability is achieved by the mixes made with both ratios when combining them with a water to cement ratio of 0.45.

For the slag, the sand to cement ratios of 2.5 and 2.75 were fixed considering that the higher skid numbers for this aggregate were obtained over the ratio of 3, however, the mixes made with this ratio were stiff, hence by lowering the sand to cement ratio, an improvement in workability was achieved as well as an increase in strength.

Since different sand to cement ratios were fixed for both lightweight and slag, separate experiments were designed. Therefore, it will not be possible to establish a comparison of results, but it will be possible to gain a better understanding of the skid phenomenon within each experiment.

Tables 10 and 11 summarize factors, levels, and final skid resistant numbers for each experiment. In addition to the five levels of latex (percentages), mixes with no admixture were included in both experiments. Both experiments

Table 10. Final Skid Numbers for Lightweight

% Latex *

SCRATIO (n)	0%	10%	20%	30%	40%	45%
n = 1.5	42	45	43	43	46	44
	46	49	44	43	45	47
	42	47	42	43	46	43
	41	44	42	44	46	44
	(42.75)	(46.25)	(42.75)	(43.25)	(45.75)	(44.50)
n = 2.0	43	44	43	44	44	43
	43	44	42	43	44	41
	43	44	40	42	44	44
	44	44	44	45	44	43
	(43.25)	(44.00)	(42.25)	(43.50)	(44.00)	(42.75)

* By weight of cement

Table 11. Final Skid Numbers for Slag

% Latex*

SCRATIO	0%	10%	20%	30%	40%	45%
n = 2.50	34	28	36	37	39	37
	37	37	35	37	39	39
	39	32	40	37	39	32
	37	31	37	36	34	36
	(36.75)	(32.00)	(37.00)	(36.75)	(37.75)	(36.00)
n = 2.75	38	41	37	40	36	39
	36	38	38	37	39	41
	36	36	38	38	37	39
	40	37	41	37	34	37
	(37.50)	(38.00)	(38.50)	(38.00)	(36.50)	(39.00)

* By weight of cement

were 2 x 6 factorial experiments, casting four specimens for each mix combination. Then each experiment included 48 observations.

3.5.1 Analysis of variance for lightweight mixes

A Foster-Burr Test for homogeneity of variances was performed on the data of Table 10, resulting in acceptance of the hypothesis that the variances within the cells were equal at 0.05 level of significance.

Then an analysis of variance was performed. The ANOVA table (see Appendix) indicates that there were no significant interactions between the factors sand to cement ratio (SCRATIO) and percentage of latex (PERLATEX) at 0.05 level. At the same level of significance, the percentage of latex had significant effects on the skid resistance properties of the lightweight mortars and with less degree, the sand to cement ratio also had significant effects.

In order to detect where those significant effects were, a Newman-Keuls comparison of means was performed. From this comparison, the best sand cement ratio was 1.5 which yielded a mean average of 44.21, the ratio of 2.0 yielded a mean average of 43.29, however, since they were averaged over 24 observations, a significant difference between them was detected at 0.05 level.

From a similar analysis it was observed that there were no significant differences between the skid means obtained with 10, 40, 45, 30 percent of latex and those percentages yielded the higher means from the first to the fourth

places respectively.

3.5.2 Analysis of variance for slag mixes

After satisfying the Foster-Burr Test for homogeneity of variances, an analysis of variance was performed on data of Table 11. The ANOVA table indicates that there were significant interactions between the sand to cement ratio and the percentage of latex, at 0.05 level. This situation made it difficult to interpret the model. Therefore, an analysis of the individual mean cells was carried out.

Because the means of each cell were based on four observations, the Newman-Keuls table indicates that there was no significant difference between the first ranked mean and the eleventh (36.00), and also there were no significant differences among all of them, hence, from the statistical point of view, any of those mixes could be selected. The twelfth ranked mean was obtained with 10% of latex and a sand to cement ratio of 2.5; unfortunately, the rubber slider of the portable skid-resistance tester was wearing out at this level, and it was replaced several swings later, so it might be that this situation was the cause for such low mean. In general, higher means were obtained over the sand to cement ratio of 2.75.

Because of the presence of the two-way interactions, a comparison of means over each level factor was not straightforward, but some useful information could be obtained.

The Newman-Keuls table to detect the best sand to cement ratio for slag indicates that the ratio 2.75 yielded the

higher mean (37.92), and this mean is significantly different than the mean yielded for the ratio of 2.50 (36.04), at 0.01 level.

Finally, the Newman-Keuls for detecting the best percentage of latex indicates that there were no significant differences among the six means, then any percentage of latex could be selected as far as skid resistant is concerned.

No detrimental effects on the skid resistance were detected when using Dow Latex 464 as an admixture. In Figure 10, the skid resistance is plotted against the percentages of latex used in the mortars.

3.5.3 Compression Strength of the Final Mixes

For each mix combination, three cubes 2 x 2 inches were tested under compression; averages of strength (psi) at 28 days appear on Tables 12 and 13.

3.5.4 Pull Out Test

An attempt was made to set up a laboratory test to evaluate the bonding capacity of thin overlays. Figure 11 is the plan for the "Pull Out Test".

Briefly, in this test a steel plate welded to a steel rod is placed into a hole of the same shape made on a small slab. Then a thin overlay (3/8 inch in this investigation) is cast and moist cured after demolding 24 hours later. Finally, at the age of 28 days, the force required to pull out the steel plate is recorded as a result.

Important points to consider in this test are:

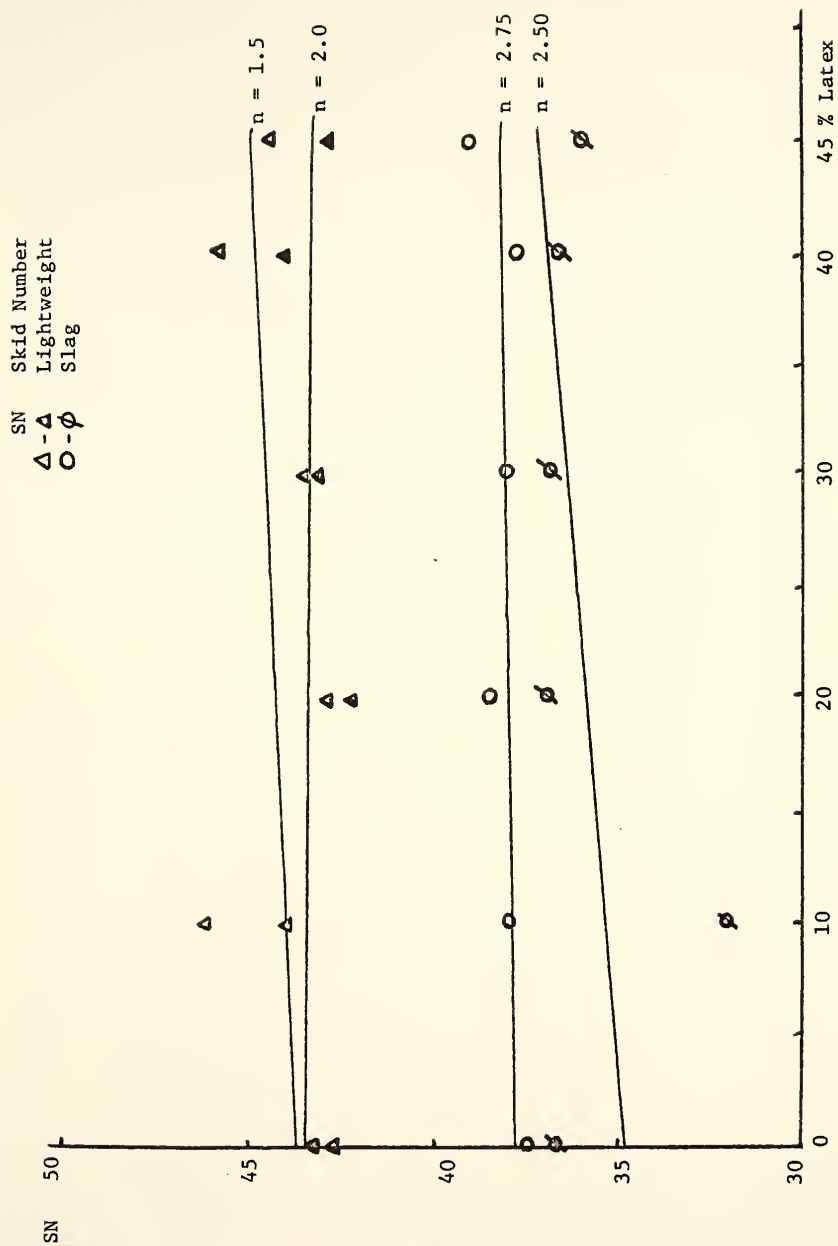


Figure 10. Effects of Latex on the Skid Resistance

Table 12. Strength of Cubes for Lightweight (psi)

SCRATIO (n)	% Latex *				
	0%	10%	20%	30%	45%
n = 1.5	4570	5010	5480	5670	6470
n = 2.0	4060	4650	4700	4750	5440
					5680

Table 13. Strength of Cubes for Slag (psi)

SCRATIO (n)	% Latex *				
	0%	10%	20%	30%	45%
n = 2.50	6290	7440	7710	9140	10190
n = 2.75	5880	6130	7050	7280	7570
					8110

* By weight of cement

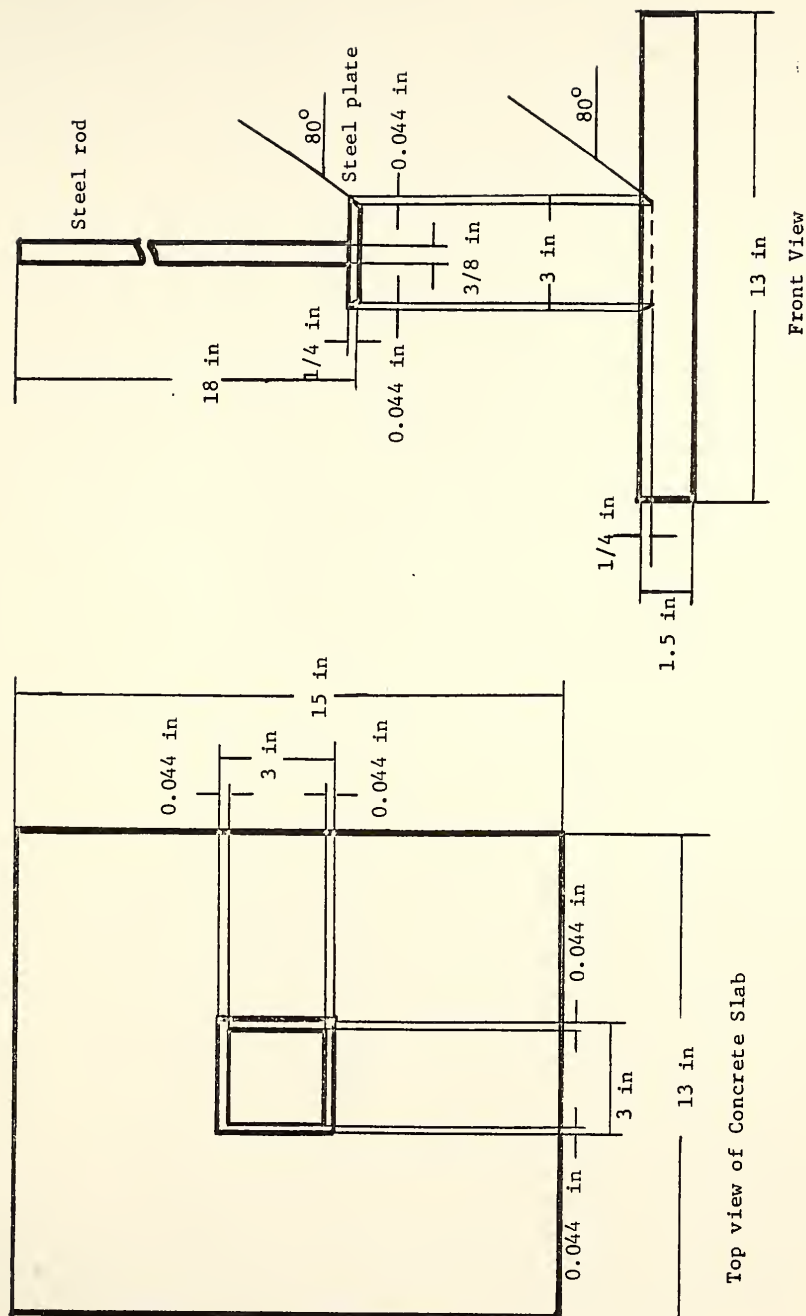


Figure 11. Plan for the "Pull Out" Test

1. The small slab has to be strong enough to insure good performance.
2. Care should be taken to expose the concrete aggregate before casting the thin overlay to avoid the superficial mortar.
3. The sharp edges of the steel plate should be greased to avoid infiltration when casting the overlay. The concrete surface has to be free of grease contamination and be wet.
4. The steel rod has to be protected from rusting when the specimen is in the moisture room.
5. The base of the slab should be as smooth as possible to insure it is level when testing.
6. The specimen has to be securely fastened to the testing machine when pulling up the steel rod. Care should be taken to insure that the load is applied vertically.

3.5.5 Pull Out Results for the Final Study

In this work two pull out specimens were cast for each mix combination; only the sand to cement ratios of 1.5 and 2.5 were investigated for both lightweight and slag

respectively. Averaged results are shown on Table 14. Figures 12 to 19 explain the procedure followed to carry out the Pull Out Test.

Good bonding was developed by the slag mixes, since the failure was by shear for all the percentages of latex.

On the other hand, fair to poor bonding was exhibited by most of the lightweight mixes. Most of these overlays felt apart failing by bonding.

Table 14. Pull Out Test Results (1b)

% Latex *

SCRATIO (n)	0%	10%	20%	30%	40%	45%	TYPEAG
n = 1.5	1060	1147	1152	1153	1163	1040	Lightweight
n = 2.5	1550	1570	1588	1647	1648	1907	Slag

* By weight of cement

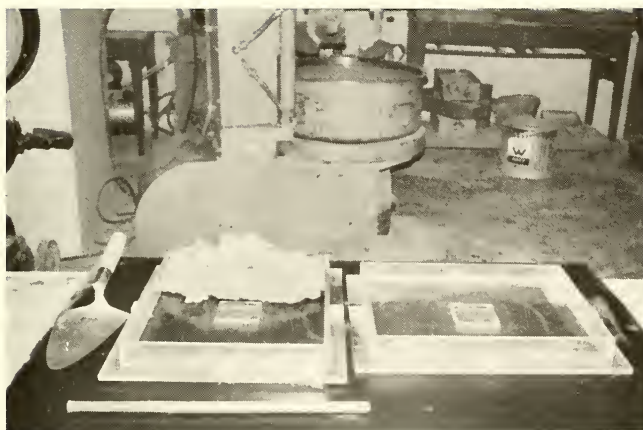


Figure 12. Casting slabs

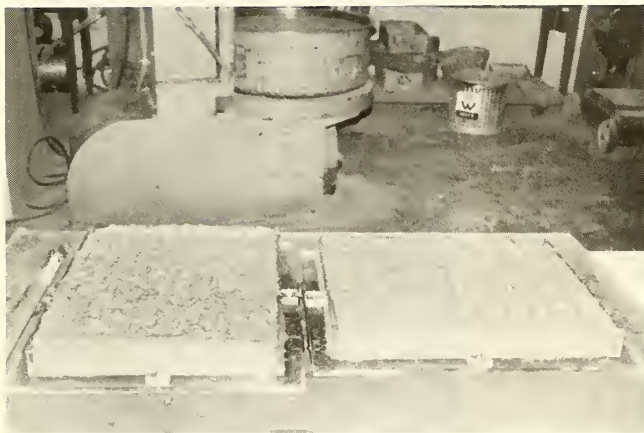


Figure 13. Finishing slabs



Figure 14. Casting the thin overlay

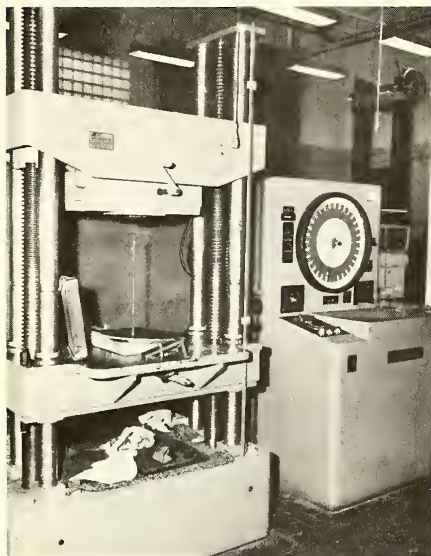


Figure 15. Testing machine

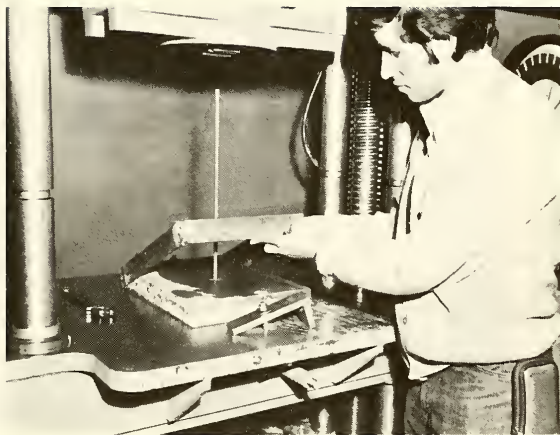


Figure 16. Fastening slab to the base of testing machine



Figure 17. Checking verticality in loading

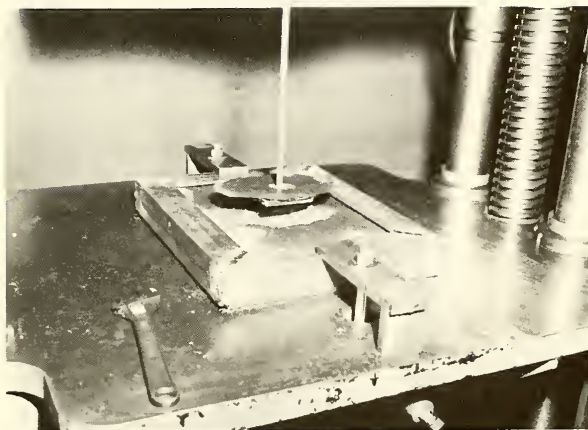


Figure 18. Typical shear failure

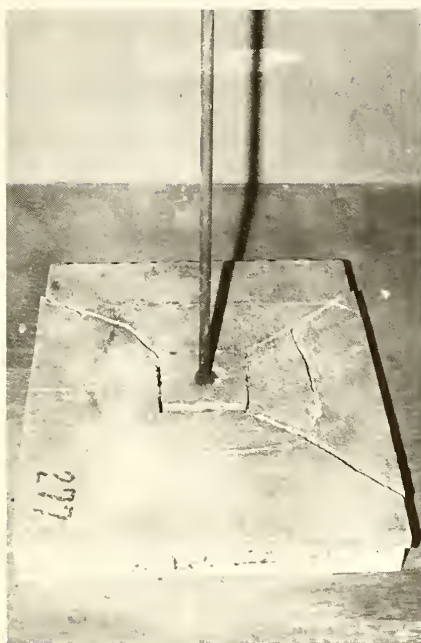


Figure 19. Typical bonding failure

CHAPTER IV

SUMMARY AND FINDINGS

4.1 Summary

A simulation of the polishing action of the traffic and skid phenomenon was carried out in the laboratory. A statistical approach was used to identify acceptable mortar mixes to be applied as a thin surfacing for improving skid resistance on concrete pavements.

From the initial factors considered, the type of aggregate turned out to be the most significant, since the skid resistance of the mixes greatly depends on the qualitative level of this factor. The other factors: sand to cement ratio, water to cement ratio and admixture all interact and their separated effects are difficult to interpret. However, an analysis of the individual cell means indicated that the higher skid numbers were reached with lightweight aggregate and slag, whereas the natural sand yielded the lower ones.

Mixes with the lower water to cement ratio namely 0.40 (by weight) yielded some of the higher skid numbers. In addition, the natural sand and slag developed better skid resistance with a sand to cement ratio of 3 (by weight), whereas the lightweight aggregate behaved satisfactorily with the ratios of 2 and 3.

The admixture Dow Latex 464 was present in the mixes which reached most of the higher skid numbers.

With the information provided by the initial study, it was decided to design two new experiments in an effort to improve workability and strength of the mixes without introducing detrimental effects on their anti-skid properties. The new experiments included the lightweight and slag aggregates, the sand to cement ratios of 1.5 and 2.0 for lightweight and the ratios of 2.5 and 2.75 for slag. In addition, the admixture latex was used at 0, 10, 20, 30, 40 and 45% of the weight of cement, and a water to cement ratio of 0.45 was adopted for all the mixes.

From this study no detrimental effects on the skid resistance were detected when different percentages of latex were used in the mixes.

The strength of the final mixes was evaluated by compression tests of 2 inch cubes at the age of 28 days. Strengths up to 10,190 psi were obtained for the mixes made of slag and up to 6,470 psi for those made of lightweight.

The bonding capacity of the mixes was evaluated by means of a "Pull Out Test". Good bonding was obtained for the mixes made up of slag with a sand to cement ratio of 2.5 and 45% of latex, the force required to pull out a section of this mortar (see Figure 18) was 1907 lb.

On the other hand, fair bonding was obtained with the lightweight aggregate, a sand to cement ratio of 1.5 and 40%

of latex, a force of 1163 lb was required under the Pull Out Test.

At the levels of latex stated above, the slag mix became sticky and somehow difficult to work with, whereas the workability of the lightweight mix was satisfactory.

4.2 Findings

1. A select mix proportion can be obtained from laboratory work to be applied as a thin surfacing for improving skid resistance on concrete pavements.
2. The British polishing machine and the portable skid tester afford a method of laboratory evaluation when simulating both polishing action of the traffic and skid phenomenon.
3. Mixes with the range of mortars can be applied as thin surface treatments on concrete pavements.
4. The primary factor that influences the skid characteristics of polished mixes is the type of aggregate.
5. Within the levels of this investigation the factors sand

to cement ratio, water to cement ratio, type of aggregate and admixture generally tend to interact in some way. However, it was detected that lower water to cement ratios and higher sand to cement ratios tend to yield better anti-skid mixes, depending upon the type of aggregate used.

6. From the fine aggregates investigated in this work, the lightweight aggregate (expanded shale) yielded the higher skid numbers, whereas those yielded by the slag and natural sand were lower.
7. Good workability was achieved by the mixes made up of slag with sand to cement ratios of 2.5 and 2.75, and a water to cement ratio of 0.45. Good workability also was obtained by the lightweight mixes with sand to cement ratios of 1.5 and 2.0, and the same water to cement ratio.
8. Both aggregates lightweight and slag developed satisfactory

skid resistance within the levels of conclusion 7.

9. No detrimental effects on the skid resistance of the mixes were detected when using Dow Latex 464 as admixture.
10. Improvement in workability, strength and water proofing properties can be obtained when using latex in the mortars. Mixtures with latex were also more easily consolidated.
11. The "Pull Out" Test can evaluate adhesion in a qualitative way, detecting either weak mixes or strong ones.
12. By means of the Pull Out Test an improvement on the bonding capacity of the mortars was detected when the percentage of latex was increased up to 45% of the cement weight. At this level of latex, the slag mix developed its highest capacity, whereas the light-weight mix developed good compression strength but low

bonding capacity; apparently the thin overlay became so strong and flexible that the bonding failure occurred before cracking.

13. The Pull Out Test showed that the slag mixes failed by shear whereas the lightweight mixes failed by bonding.
14. From the statistical point of view it is not possible to compare the skid results for each experiment since they were designed for factors having different levels.
15. All the experiments were designed without considering the next factors:
 - a) different operators running the same test
 - b) experience of operator
 - c) strict temperature control when casting or testing
 - d) control over the interaction effects when the

rubber slider of the
portable skid tester
is renewed

Unfortunately in this research, the labor on the initial and final studies were performed by different operators. In addition, the rubber slider had to be renewed during the final study, obviously the skid numbers obtained with a worn slider tend to be lower than those obtained with a new one.

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APPENDIX
STATISTICAL DATA

Note: The Appendix material is not included in this copy of this report. It is available on request from the address noted below at the costs of duplication and mailing:

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